

APPENDIX A: STRUCTURAL SAFETY ASSESSMENT OF EXISTING METAL GUARDRAILS

A-1. Introduction

a. Concern over the protection of both employees and the general public against accidental injuries has greatly increased in recent years. As a result, the proper design of protective devices for this purpose has become more crucial. Prominent among such protective devices are railings of all kinds, commonly referred to as “guardrails” or “vertical barriers.” For years, railings have been built to resist a certain amount of lateral loading as variously specified by local building codes and the USACE. However, with the advent of many recent Federal regulations governing the design of railings, more careful consideration must be given to the railings’ structural design and physical features.

b. Although the differences between railing design requirements among the building codes are now becoming fewer, past railing specifications have been widely varied, with some much more stringent than others in regard to structural requirements. As a result, it is possible that some existing guardrails are structurally inadequate according to the current USACE specifications. Since numerous USACE projects make extensive use of metal guardrail systems for protection of life, this possibility must be given careful attention.

c. This ETL provides guidance for the engineer to use in assessing the structural safety of existing metal railing. It is primarily concerned only with the most basic and most common type of utilitarian railings, i.e., those constructed with metal pipe or tubing.

d. The manual EM 385-1-1 prescribes the safety and health requirements for all USACE activities and operations. Section 21.B of the October 1992 edition of the manual contains the requirements for standard guardrails and handrails.

A-2. Structural Safety Assessment

a. General.

(1) Considerable attention has been given to the design of guardrails by industry associations such as the NAAMM (National Association of Architectural Metal Manufacturers) and NOMMA (National

Ornamental and Miscellaneous Metals Association). The majority of the information set forth herein was taken directly from their manuals and adapted for the analysis of existing railings, instead of the design of new railings. The procedures are basically the same, except, in an analysis, the engineer must be careful to determine actual existing conditions (such as dimensions, section sizes, and existing condition) in order to make an accurate safety assessment.

(2) In a structural design, the sizes (i.e., section modulus) of load-carrying members are determined based on the applied loadings, allowable stresses, and member lengths and spacings. In a structural analysis, the dimensions, etc., of the system are already known and the applied stresses are compared with the allowable stresses of the members to determine whether the system is safe. For guardrail systems, the areas of greatest structural concern are bending moments in the rails and posts and anchorage stresses at the connection of the posts to the supporting platform. Therefore, for the structural analysis of an existing guardrail system, the following quantities must be defined:

- Existing condition of the railing.
- Material type and properties, section properties, lengths, and spacings of railings and posts.
- Required loadings.
- Post anchorage details.
- Presence of reinforcing inserts at base of posts.

(3) The reconnaissance of these items and their application to structural safety analysis are described in the following paragraphs.

b. Existing condition.

(1) Prior to any structural safety assessment, the existing condition of the in-place railing must be determined. This should be accomplished through careful onsite inspection of the railing. Check the guardrail members for any signs of internal or external corrosion (which causes reduced cross-section) or

cracks. High stress areas, such as at railing and post support points, should be given careful inspection. Members that are susceptible to debris and water collection, such as at the base of posts, should be inspected internally for corrosion. If section loss (internal or external) has occurred, the remaining section should be carefully measured and those values used in the structural analyses. If cracking is observed, those particular members should be immediately repaired or replaced.

(2) The condition of the guardrail's anchorage to its supporting platform must also be checked. Verify that anchor bolts are all still in place, tightly anchored, and in good condition. If welded, check the welds for cracks and deterioration. Welded aluminum is particularly susceptible to cracking caused from differential expansion and contraction between dissimilar metals.

c. Material properties.

(1) Guardrails are constructed from a wide range of metals. Mechanical properties and allowable design stresses of some of the more commonly used metals are provided in Table A-1. Carefully note that the allowable tensile stresses for tempered (T-type) aluminum alloys must be reduced at all locations within 25 mm (1 in.) of welds.

(2) The allowable stresses shown in Table A-1 are based on recommendations from NAAMM (1985) and NOMMA (1986). The NAAMM manual notes that some designers feel that, particularly in the case of high concentrated loads such as the 890-N (200-lb) load specified by the USACE, the use of higher allowable stresses may be justified. This is based on the fact that this type of loading will be of a momentary rather than sustained nature. The validity of this position largely depends upon what is considered acceptable railing performance and how "failure" is defined. The purpose of safety regulations is to ensure that the railing provides protection against persons falling, and the railing need not remain in perfect alignment to perform this function. If a slight permanent deformation under this conservative loading is deemed acceptable, this would theoretically permit the use of an allowable bending stress approaching the yield stress. Of course, the use of yield stress for the allowable stress is not easily palatable to engineers, who must always be conservative. However, actual physical testing has repeatedly demonstrated that securely anchored pipe railings are

capable of carrying, with little or no permanent deformation, loads much greater than those computed on the basis of the conservative conventional bending stresses. With these facts in mind, the engineer must make a rational decision as to the allowable bending stress. For USACE guardrails that are located in areas of high public access, such as daily guided tour stops, the conservative and conventional allowable stresses provided in Table A-1 should be used. For guardrails in low traffic areas, where railings are rarely leaned upon, an allowable stress up to $0.85f_y$ may be used at the engineer's discretion. However, due to the often detrimental effects of welding aluminum, only the allowable stresses shown in Table A-1 should be used for welded aluminum railing, regardless of the railing usage.

d. Sectional properties.

(1) Pipe is produced in a variety of sizes or "schedules," of which those more commonly used for railings are listed in Table A-2. The sections shown in Table A-2 are by no means all-inclusive. Many manufacturers have proprietary sections that have unique properties. Information on these sections can often be obtained from supplier's catalogs or from industry associations. In steel pipe, Schedule 40 is known as "Standard Weight" and Schedule 80 as "Extra Strong." Standard weight is measured by i.p.s. (iron pipe size), which designates its nominal size. Unless otherwise specified, Schedule 40 is normally supplied in steel, aluminum, or copper pipe and Schedule 5 in stainless steel tubing.

(2) Round tubing is also available in all four metals. Tubing differs from pipe in that it may have thinner or thicker walls and is measured by a different system, which designates the outside diameter and the wall thickness. The wall thickness is designated in decimal inches or gauge number. Size designations may differ somewhat with the different metal.

(3) For structural analyses of existing railing, the section properties of the pipe must be carefully obtained. This can be accomplished through use of reliable as-built records on the project or through careful field measurements. As-built records, backed up by field measurements, are the most desirable combination since accurate section properties are essential to an accurate structural analysis. Accurate field measurements are also important since as-built records will only list "nominal" sizes. The ASTM standards for pipe and tubing extrusions provide

Table A-1
Mechanical Properties and Allowable Design Stresses
(Source: NAAMM and NOMMA)

Metal and Alloy	Allowable Stress MPa	Minimum Yield MPa	Elastic Modulus MPa x 10 ³
Carbon Steel Pipe:			
A53, Type F	124	172	200
Types E and S, Grade A	149	207	200
Types E and S, Grade B	172	241	200
Carbon Steel Struc. Tubing:			
A500, Grade A	164	228	200
A500, Grade B	207	290	200
A500, Grade C	228	317	200
A501	179	248	200
Aluminum Pipe:			
6063 T5, T52	79*	110	69
6063 T6	124*	172	69
6063 T832	165*	241	69
6061 T6	165**	241	69
Stainless Steel Tubing:			
Annealed, Types 302, 304, and 316	124	207	193
Unannealed Types 302, 304, and 316	207	345	193

Note: American Iron and Steel Institute (1985) specifies $f_b = 0.72f_y$. It also specifies that the diameter-thickness ratio of hollow circular sections shall not exceed $3300/f_y$. For aluminum, allowable stresses are those specified by the Aluminum Association; for stainless steel and copper, the allowable stresses shown are $0.60f_y$.

* Reduce allowable stress to 55 MPa within 25 mm of any weld.

** Reduce allowable stress to 97 MPa within 25 mm of any weld.

Table A-2
Pipe Section Properties
(Source: NAAMM and NOMMA)

Nominal Size	Schedule No.	Outside Diameter mm	Inside Diameter mm	Wall Thickness mm	Area mm ²	Section Modulus mm ³	Moment of Inertia mm ⁴ x 10 ³
32	5	42	39	1.7	210	2,050	43
	10		37	2.8	343	3,160	67
	40		35	3.6	431	3,850	81
	80		32	4.9	569	4,770	101
38	5	48	45	1.7	242	2,720	66
	10		43	2.8	395	4,260	103
	40		41	3.7	515	5,340	129
	80		38	5.1	689	6,750	163
51	5	60	57	1.7	305	4,340	131
	10		55	2.8	501	6,880	208
	40		53	3.9	693	9,190	277
	80		49	5.5	953	11,980	361

tolerances within which the section sizes can deviate from the nominal dimension. While these allowable dimension variations may appear small and insignificant, they could conceivably affect the overall section properties, and thus the available strength of an already marginal structural member.

(4) Also note that since the analysis is being conducted on railing which may have been in service for years, its possible deterioration must be considered. This can only be determined through careful field reconnaissance and measurements. The railing can deteriorate from both the outside where it is readily visible, or from the inside where it is not readily visible. Deteriorated railing can be accounted for in the structural analysis by appropriately reducing the available cross-section of the member(s) or by reducing the allowable stresses.

(5) Reinforcing inserts are sometimes used at the base of the guardrail posts to shorten the length of the posts, thereby increasing the allowable loads on the railing. The presence of these items must be established for an analysis since it will significantly affect the post's available load capacity.

e. Loadings.

(1) The most critical loads for guardrails are those which are applied horizontally since these produce the maximum bending moment on posts. The maximum bending moment on a rail member, under a concentrated load, results when the load is applied at the center of the rail span. Posts act as columns in resisting vertical loading on rails, and as vertical cantilever beams in resisting horizontal loading on either the rails or the posts themselves. Usually it is the bending moment due to the cantilever beam action under horizontal loading that produces the highest stress.

(2) EM-385-1-1 specifies that "the anchoring of posts and framing of members for all guardrails shall be of such construction that the completed structure shall withstand a load of at least 890 N (200 lb) applied in any direction at any point on the toprail without failure and with a minimum of deflection."

(3) This concentrated loading is the same as that specified by the Federal Occupational Safety and Health Administration (OSHA) for railings in places or areas where persons are employed. As a

result, this is likely the most applicable loading for most USACE facilities where large groups of people (such as guided tours) are generally not expected. Other widely accepted building codes are directed more toward the restraint of large groups of people at one time. They specify uniform loadings over the length of the rails, which are considered to represent the force exerted by tightly grouped persons leaning on or pressed against the railing. Such loading requirements range from 292 to 730 N/m (20 to 50 lb/ft), usually applied horizontally to the top rail. Some codes require also that railing in certain locations be designed to carry loads as high as 100 lb/ft applied vertically downward on the rails.

(4) Because EM 385-1-1 governs all of the Corps' safety requirements, the 890-N (200-lb) concentrated load criterion is the minimum that railings on USACE facilities must meet. However, based on the above discussion and knowledge of specific railing demands, the USACE engineer may determine that other loading criteria are more applicable to a particular situation. However, the engineer must always meet the EM criteria as a minimum.

f. Post analysis.

(1) The following discussion and calculations are applicable to free-standing, straight run railings with uniform post spacing. Lateral bracing, curving, or attachment to other structures may reduce bending stresses substantially, which may be taken into account. A typical guardrail system is depicted in Figure A-1.

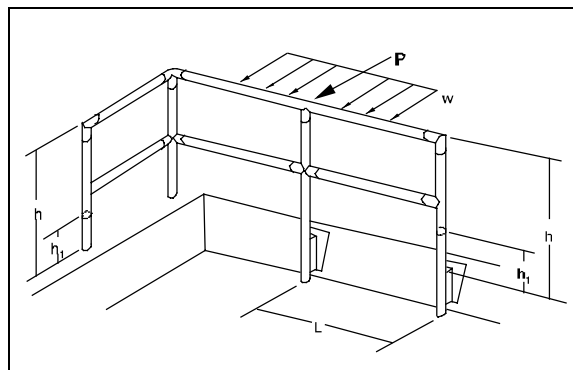


Figure A-1. Typical guardrail system

(2) Concentrated rail loading P , as specified by the USACE, is assumed applied at any point along

the railing. The maximum bending moment M in the post will occur at its point of attachment to the platform, at a distance h from the top railing. In continuous, multispan railing installations (most common), the horizontal load applied to the top rail at any one post is distributed, in part, to the adjoining posts on either side. Therefore, in many instances, the loading carried by each post is actually considerably less due to load sharing among adjacent posts. Load distribution is determined by stiffness of the rail relative to stiffness of the posts and by the total number of spans in the run. For a straight run of railing, the load-proportion factor P_f may be determined from the graph in Figure A-2, based on the stiffness ratio R , which is determined as:

$$R = \frac{k_{Rail}}{k_{Post}}$$

where

$$k_{Rail} = \frac{E_{Rail} \cdot I_{Rail}}{L}$$

$$k_{Post} = \frac{E_{Post} \cdot I_{Post}}{h}$$

and

k = stiffness

E = modulus of elasticity

I = moment of inertia

L = length

The formula used in developing this graph assumes that all posts are of identical material and section. If one or both ends of the rail are free-standing, the "end-loaded" condition must be assumed. If both ends of the run are braced laterally by a change in direction or attachment to a firm structure, the "center-loaded" proportion factor may be used. The stiffness ratio is plotted on the graph to obtain the load proportion factor. This factor is then multiplied by the total load to determine the applied moment on a single post as:

$$M_{applied} = P \cdot h \cdot P_f$$

or as

$$M_{applied} = P \cdot (h - h_1) \cdot P_f$$

for a concentrated load with a reinforcing insert of height h_1 at the post base (refer to Figure A-1). If end posts differ from intermediate posts in strength, the load-distribution pattern becomes indeterminate and end posts should then be designed to carry 100 percent of the concentrated load. Intermediate posts may then be designed to the "center loaded" condition. For single span railings (i.e., only two end posts) or where the top rail is completely flexible (such as a cable), the posts are assumed to carry the entire applied loading.

(3) Uniform rail loading is assumed to apply over the full length of the railing. Therefore, no load distribution occurs among posts. The load carried by a single post is thus equal to the load per unit length w multiplied by the post spacing, or span. End posts carry only half as much rail load but, for practical reasons, are generally made of the same pipe size as that required for the intermediate posts. The maximum applied moment for this load case is thus:

$$M_{applied} = w \cdot l \cdot h$$

(4) For all loadings, the applied bending stress $f_{applied}$ is calculated as:

$$f_{applied} = \frac{M_{applied}}{S}$$

where S = section modulus. Applied bending stress can be compared to the allowable bending stress f_{allow} as discussed in paragraph A-2c above. The applied stress should always be less than the allowable stress.

g. Rail analysis. A concentrated load applied to a rail exerts its greatest bending moment when applied at mid-span. The moment is determined by the load P , and the length of the span L , and is calculated as:

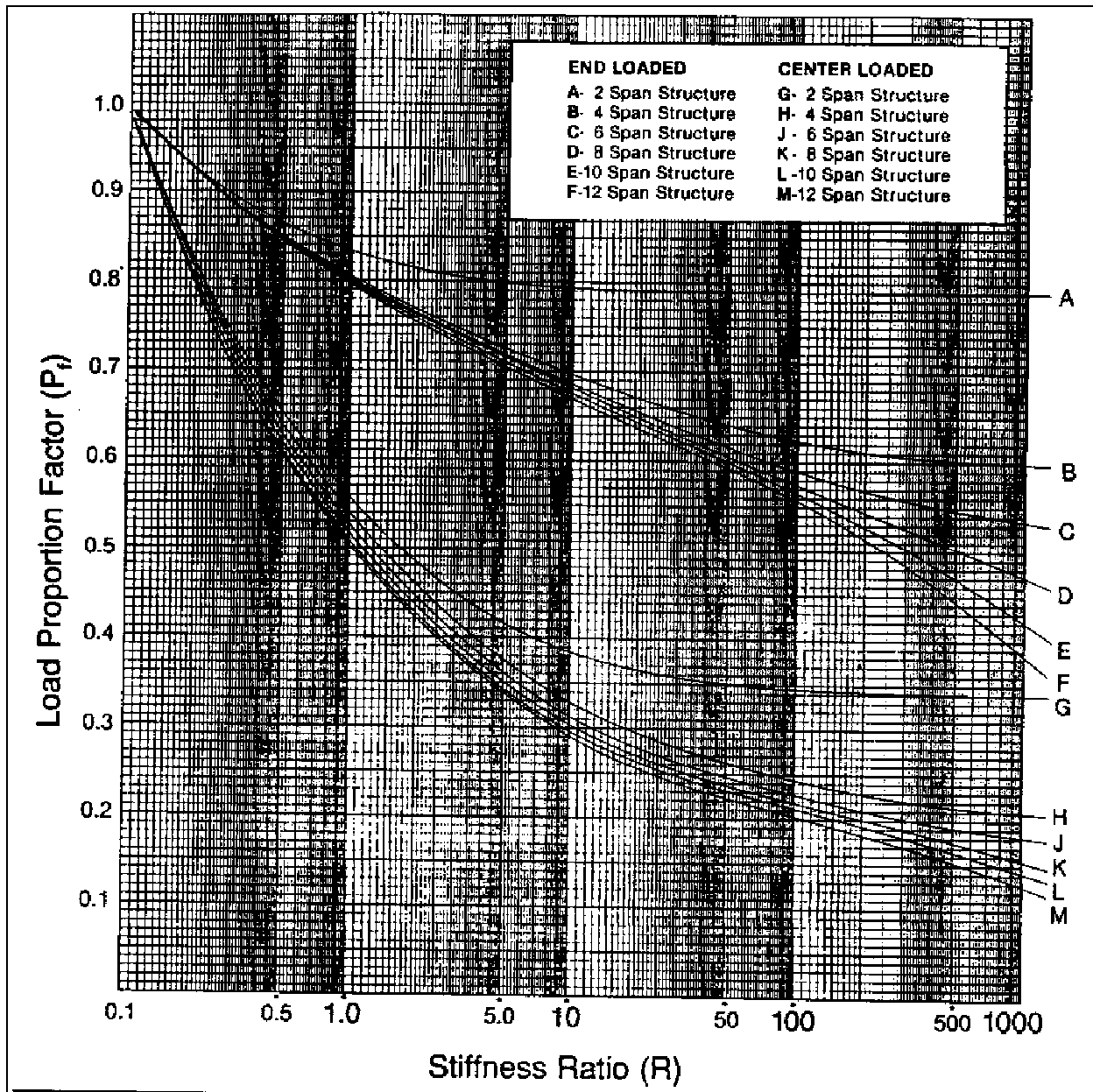


Figure A-2. Railing load distribution data (source: NAAMM)

$$M_{\text{applied}} = \frac{P \cdot L}{K}$$

where

$K = 4$ for one span

$K = 5$ for two or more spans

For uniformly distributed railing loads, the moment is calculated as:

$$M_{\text{applied}} = \frac{w \cdot L^2}{K}$$

where

w = railing load per unit length

K = 8 for one or two spans

K = 9.5 for three or more spans

For all loadings, the applied bending stress $f_{applied}$ is calculated as:

$$f_{applied} = \frac{M_{applied}}{S}$$

and compared to the allowable bending stress f_{allow} as discussed in paragraph A-2c above. The applied stress should always be less than the allowable stress.

h. Anchorage analysis.

(1) While all of the above calculations may show a guardrail system to be structurally safe, the system will still be only as strong as the anchorage to its supporting structure. Whatever the supporting structure -- metal, masonry, or wood -- attachment procedures are much the same; only the type of fastener will vary. A railing can be mounted on the fascia or stringer of a platform or stair, can be set into the floor or stair tread, or can be mounted on the floor or tread surface with a mounting fixture.

(2) When railings are set into concrete or masonry floors or treads, the post receiving holes should generally be at least 13 cm (5 in.) deep in order to provide ample post support. The edges of the holes should be located at least 9 cm (3-1/2 in.) from the edge of concrete or masonry. The ends of the aluminum posts should be coated with bituminous paint, methacrylate lacquer, zinc chromate primer, or other suitable coating to protect against accelerated corrosion caused by contact with concrete, grout, or dissimilar metals. For railings mounted on the surface of the floor or stair tread, either lateral bracing is required or a heavy-duty floor flange, designed to withstand the required loading and to support and reinforce the post, must be used.

(3) Required fastener capacity can be determined by computing the moment about a fastening or support and comparing to the allowable bolt pullout force, which is listed by the manufacturers of the fasteners. The applied bolt pullout force is

basically the same for all mounting arrangements and is calculated as:

$$f_{applied} = \frac{P \cdot h}{d}$$

for the mounting arrangement depicted in Figure A-3a, and as:

$$f_{applied} = \frac{P \cdot (h + a + d)}{d}$$

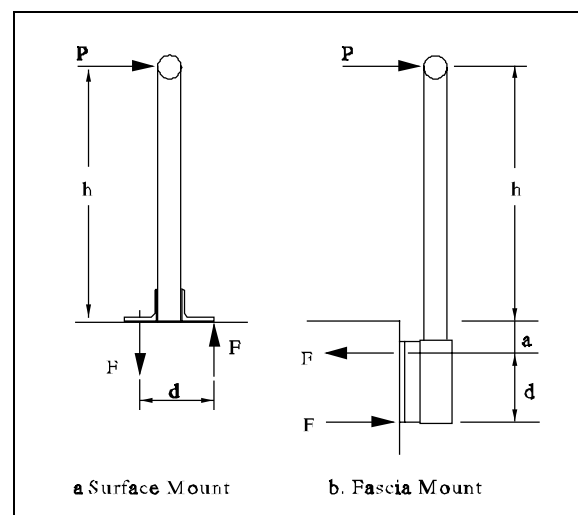


Figure A-3. Guardrail mounting methods

for the mounting arrangement depicted in Figure A-3b. A safety factor of 1.65 should be applied to these values. The applied pullout force is then compared to the allowable pullout force (supplied by the manufacturer), which is calculated as:

$$f_{allow} = F \cdot n$$

where n = number of fasteners in line. Because of the uneven quality of concrete, it is recommended that a safety factor of 4 be applied to the allowable pullout force. However, many manufacturers have already applied appropriate safety factors to their recommended pullout values, and additional safety factors may not be necessary. The manufacturers' recommendations for anchor embedment length and hole edge distance should also be carefully checked.

A-3. Example Problem

a. *Problem definition.* The guardrail in Figure A-4 has 10 spans and has a change of direction at both ends. Both the toprail and posts are 38-mm, schedule 40 pipe, from 6061 T6 Aluminum. The posts are spaced at 1.2 m on center and are welded to a round aluminum plate with a 15 cm diameter ($d = 11.4$ cm). The plate is attached to a concrete surface via four symmetrically spaced 10-mm-diam wedge-type concrete anchors. The manufacturer-specified pullout strength for the anchors is 18.2 kN per anchor (including the safety factor). Determine whether the guardrail system can safely withstand the USACE-specified 890-N (200-lb) horizontal concentrated loading.

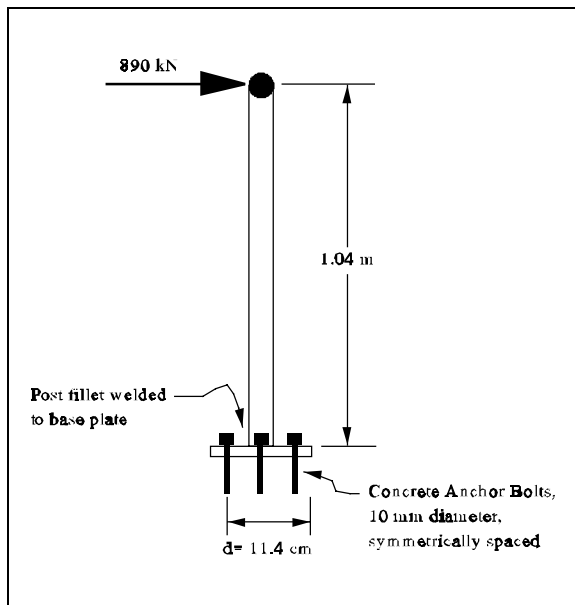


Figure A-4. Railing for example problem

b. *Existing condition.* Prior to any analysis, the guardrail system should be carefully inspected for deterioration as described in paragraph A-2b. For this example, it will be assumed that the guardrail system is in good condition and thus no reductions will be made to the allowable stresses or section properties.

c. *Post analysis.*

(1) From Table A-1, the allowable stress for Aluminum 6061 T6 pipe within 25 mm (1 in.) of a weld (Refer to footnote in Table A-1) is:

$$f_{allow} = 97 \text{ MPa}$$

(2) From Table A-2, the section properties for the post are:

$$I = 129,000 \text{ mm}^4$$

$$S = 5,340 \text{ mm}^3$$

(3) Determine the load proportion factor P_f based on the relative stiffness R :

$$\begin{aligned} R &= \frac{k_{Rail}}{k_{Post}} = \frac{\frac{E_{Rail} \cdot I_{yRail}}{L}}{\frac{E_{Post} \cdot I_{Post}}{h}} \\ &= \frac{(69 \times 10^3 \text{ MPa})(129,000 \text{ mm}^4)(1,040 \text{ mm})}{(69 \times 10^3 \text{ MPa})(129,000 \text{ mm}^4)(1,220 \text{ m})} \\ &= 0.85 \end{aligned}$$

From curve "L" of Figure A-1, $P_f = 0.53$

(4) Calculate the applied moment:

$$\begin{aligned} M_{applied} &= P \cdot h \cdot P_f \\ &= (890 \text{ N})(1,040 \text{ mm})(0.53) \\ &= 491,000 \text{ N} \cdot \text{mm} \end{aligned}$$

(5) Compare applied stress to allowable stress:

$$\begin{aligned} f_{applied} &= \frac{M_{applied}}{S} = \frac{491,000 \text{ N} \cdot \text{mm}}{5,340 \text{ mm}^3} \\ &= 92 \text{ MPa} < (f_{allow} = 97 \text{ MPa}) \Rightarrow \text{Good} \end{aligned}$$

d. *Railing analysis.*

(1) Calculate the applied moment:

$$\begin{aligned} M_{applied} &= \frac{P \cdot L}{5} = \frac{(890 \text{ N})(1,220 \text{ mm})}{5} \\ &= 217,000 \text{ N} \cdot \text{mm} \end{aligned}$$

(2) Compare applied stress to allowable stress:

$$f_{\text{applied}} = \frac{M_{\text{applied}}}{S} = \frac{217,000 \text{ N} \cdot \text{mm}}{5,340 \text{ mm}^3}$$

$$= 41 \text{ MPa} < (f_{\text{allow}} = 165 \text{ MPa}) \Rightarrow \text{Good}$$

e. *Anchorage analysis.*

(1) Calculate the applied force:

$$f_{\text{applied}} = \frac{P \cdot h}{d} = \frac{(890 \text{ N}) (1,040 \text{ mm})}{114 \text{ mm}}$$

$$8.1 \text{ kN} \cdot SF = (8.1) (1.65) = 13.4 \text{ kN}$$

(2) Compare applied force to allowable force:

$$f_{\text{allow}} = F \cdot n = (18.2 \text{ kN}) (1)$$

$$= 18.2 \text{ kN} > (f_{\text{applied}} = 13.4 \text{ kN}) \Rightarrow \text{Good}$$

A-4. Load Testing of Guardrail Systems

If the analytical procedure discussed above shows the applied stresses to be grossly higher than the allowable stresses, an unsafe guardrail system is indicated and upgrade and/or replacement actions should be initiated. However, if the calculations indicate only a marginal system, an in-situ load test of the guardrail system may be warranted since the above analytical procedure is quite conservative in most cases. ASTM specification E 935-92 provides guidelines for this type of test in a laboratory environment. No standard test device exists for the application of this test in a field environment and thus the device and test setup must be designed by the responsible engineer using ASTM E 935 as a guideline.